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The origin of pulsar velocities.

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Abstract

We have recently proposed an explanation for the birth velocities of pulsars as resulting from asymmetries due to neutrino oscillations in the cooling protoneutron star. A specific prediction of this mechanism is that the correlation of velocities and magnetic fields should be stronger for slowly rotating neutron stars and weaker for those whose periods are less than 1 s. A remarkable agreement of this prediction with the data favors the oscillation mechanism over the alternative explanations for the proper motion of pulsars.

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Pulsars exhibit rapid proper motions [1, 2] characterized by a mean birth velocity of 450 ± 90 km/s. The origin of these motions has been the subject of intensive studies and several possible explanations have been proposed. First, a substantial “kick” velocity may result from the asymmetries in the collapse, explosion, and the neutrino emission affected by convection [3]. Second, evolution of close binary systems may also produce rapidly moving pulsars [4]. Alternatively, it was argued [5] that the pulsar may be accelerated during the first few months after the supernova explosion by its electromagnetic radiation. The last two explanations seem to be disfavored by the data [6, 7].

We have recently shown [8] that if one of the neutrinos has a mass of a few hundred electron volts, the neutrino oscillations biased by the magnetic field will cause a change in the shape of the neutrinosphere making the momentum distribution of the outgoing neutrinos asymmetric. The resulting recoil velocity of the neutron star is in good quantitative agreement with observations.

If the “kick” velocities are, in fact, related to neutrino oscillations, they provide a way to determine the neutrino mass in the range currently inaccessible to collider and other experiments. This would have important ramifications for both particle physics and cosmology. It is, therefore, important to focus on those aspects which may distinguish this explanation from possible alternatives. One specific prediction of the oscillation mechanism is that the momentum asymmetry is proportional to the magnetic field inside the neutron star. As we show below, for the pulsars with relatively large periods of rotation (of the order of seconds), this results in a correlation between the pulsar velocity v and its magnetic field B . On the other hand, for those neutron stars which rotate relatively fast, the $B - v$ correlation is obscured by the averaging of the force acting on a pulsar and is much less significant statistically. We demonstrate that this feature, that the $B - v$ correlation is strong for slowly rotating pulsars but is weak for faster ones, is in good agreement with the data. This is a strong evidence in favor of the oscillation mechanism [8].

Originally, the $B - v$ correlation [5, 6] was reported for a sample of 26 pulsars [6] (irrespective of their periods of rotation) and became the subject of several theoretical studies concerning its origin [5, 6, 9]. However, as the information about new pulsars became avail-

able, the $B - v$ correlation became only marginally significant [10]. (It was also observed [10] that there is no correlation among the pulsars which are younger than 3 Myr. We will reexamine the significance this observation below.) Another reason why this correlation may be important is because it can also help solve another long-standing puzzle, that of the provenance of the γ -ray bursts [11]. In this letter we study the dependency of the $B - v$ correlation on the rotation speeds of pulsars and compare it to the theoretical predictions [8].

The basic idea of the oscillation mechanism is the following. Neutrinos emitted during the cooling of a protoneutron star have total momentum, roughly, $10^2 - 10^3$ times the momentum of the proper motion of the pulsar. A 0.1% to 1% anisotropy in the distribution of the neutrino momentum would result in a “kick” velocity consistent with observation. In the dense neutron star an electron neutrino, ν_e , has a shorter mean free path than ν_μ , ν_τ , or any of the antineutrinos. If one of the latter, *e. g.*, ν_τ , undergoes a resonant oscillation into ν_e , above the τ -neutrinosphere but below the e -neutrinosphere, it will be absorbed by the medium. Therefore, the *effective* τ -neutrinosphere in this case is determined by the point of resonance. The latter is affected by the magnetic field in such a way, that the resonance occurs at different depth for the neutrinos emitted with a velocity parallel to \vec{B} as compared to those whose velocity is anti-parallel to \vec{B} . Therefore, the τ -neutrinos will come out from the regions of different temperatures, and will carry different average momenta, depending on the direction of their velocity relative to \vec{B} .

The resulting asymmetry in the momentum distribution is estimated to be [8]

$$\frac{\Delta k}{k} = 0.001 \left(\frac{3 \text{ MeV}}{T} \right)^2 \left(\frac{B}{3 \times 10^{13} \text{ G}} \right) \quad (1)$$

During the cooling stage of the protoneutron star, the τ -neutrinos come out with the average energy $\approx 10 \text{ MeV}$ [13], which corresponds to the temperature of $\approx 3 \text{ MeV}$. We see that the observed pulsar velocities, which require $\Delta k/k$ to lie between 0.001 and 0.01 can be explained by the values of B from $3 \times 10^{13} \text{ G}$ to $3 \times 10^{14} \text{ G}$.

The magnetic fields at the surface of the neutron stars are estimated to be of order $10^{12} - 10^{13} \text{ G}$ [12]. However, a (toroidal) magnetic field inside the pulsar may be as high

as 10^{16} G [12]. The existence of such a strong magnetic field is suggested by the dynamics of formation of the neutron stars, by the stability of the poloidal magnetic field outside the pulsar, as well as by the fact that the only star whose surface field is well studied, the Sun, has magnetic field below the surface which is 10^3 larger than that outside. (This strong magnetic field causes the sun spots when it penetrates the surface.)

It is clear from equation (1) that the deformations of the neutrinosphere due to neutrino oscillations biased by the magnetic field can result in the asymmetry of the neutrino flux necessary to give the pulsar a “kick” velocity consistent with the data.

The direction of the recoil momentum is along the \vec{B} direction and is inclined to the axis of rotation at all times. In the limit of a very slowly rotating pulsar, the birth velocity should be correlated with the strength of the magnetic field. However, if the neutron star spins rapidly about $\vec{\Omega}$, the angular velocity vector, the average force is non-zero only in the direction of $\vec{\Omega}$. If the angle between \vec{B} and $\vec{\Omega}$ is $\alpha(\vec{B}, \vec{\Omega})$, the same “kick” velocity will be generated for different values of $|\vec{B}|$, as long as the product $\{|\vec{B}| \cos \alpha(\vec{B}, \vec{\Omega})\}$ is the same. Clearly, since $\alpha(\vec{B}, \vec{\Omega})$ is random, the $B-v$ correlation in this case can be only as strong as the correlation between a random vector’s length and its third component. Thus only the pulsars whose rotation is relatively slow will exhibit a significant correlation between B and v .

The time scale is set by the duration of the neutrino emission and the rate at which the neutrino flux diminishes. The cooling of a protoneutron star takes about ten seconds [13], during which the neutrino flux continuously decreases. The characteristic time scale on which the neutrino flux remains constant is, therefore, $T \sim$ few seconds. If the period of rotation $P \gg T$, one expects B and v to be correlated. If, on the other hand, $P \ll T$, the average force acting on a neutron star in the direction orthogonal to $\vec{\Omega}$ is zero, and the $B - v$ correlation is weak.

Unfortunately, there are not enough pulsars with large periods to form a statistically meaningful sample to test the correlation in the $P \gg T$ limit. However, a generic prediction of the oscillation mechanism is that the $B - v$ correlation should become increasingly more significant as the period of rotation approaches a few seconds.

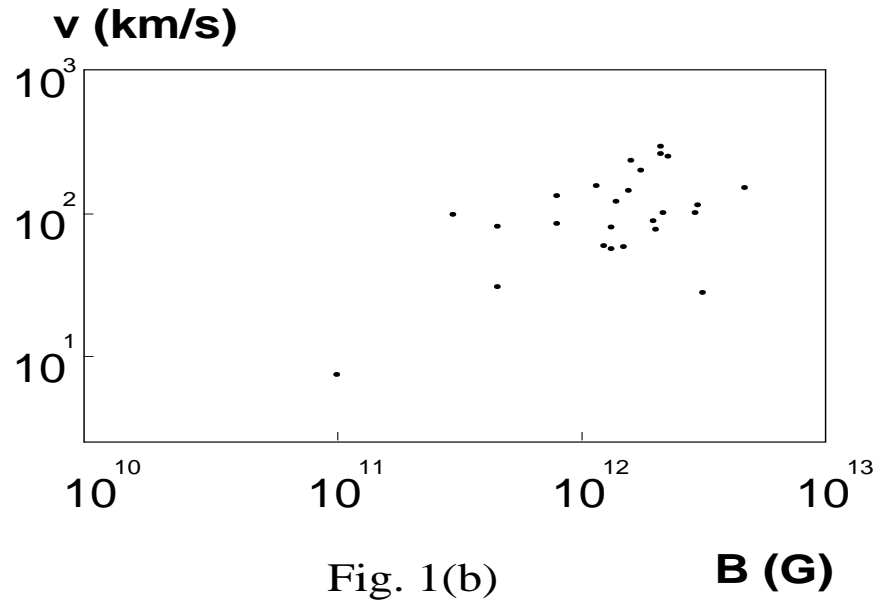
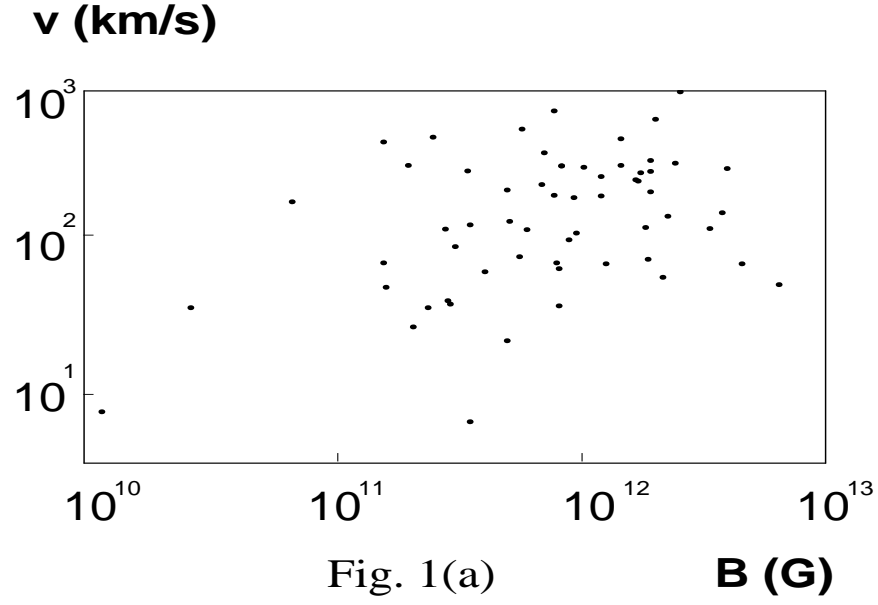


Figure 1: The $B - v$ correlation is weak for the subset of 61 pulsars (a) with periods of rotation $P < 1$ s, but is significant for the remaining 26 pulsars (b), whose periods $P > 1$ s.

This prediction is confirmed by the data as shown in Figure 1, where the data is plotted for a set of 87 pulsars [14] whose proper motions are known. For the pulsars with $P < 1$ s (Fig. 1(a)), the correlator $c(B, v) \equiv \langle B - \bar{B}, v - \bar{v} \rangle / (\langle B - \bar{B}, B - \bar{B} \rangle \langle v - \bar{v}, v - \bar{v} \rangle)^{1/2} = 0.39$. On the other hand, for the pulsars with $P > 1$ s, $c(B, v) = 0.58$ (Fig. 1 (b)), which is significantly greater. If one restricts the sample to those pulsars with $P > 1.3$ s, the correlation increases further to $c(B, v) = 0.77$. The Spearman correlation coefficients for the $P < 1$ s, $P > 1$ s, and $P > 1.3$ s samples are 0.33, 0.44 and 0.58 respectively, all significant at more than 98% confidence level. Such steady increase in the correlation with the period of rotation is precisely what one would expect from the oscillation mechanism [8].

The age τ_s of the pulsars may play an important role in the statistical analysis because of various possible selection effects. It was argued [10] that the subset of pulsars younger than 3 Myr is a better representative of the pulsar birth velocities. We found similar increase in the $B - v$ correlation for this subset of pulsars: $c(B, v) = 0.01$ for $P < 1$ s, while $c(B, v) = 0.59$ for $P > 1$ s (although there are only 5 pulsars in the latter category). This is again in agreement with our theoretical predictions.

We believe, however, that the set of pulsars with $\tau_s < 3$ Myr may not represent the distribution of birth velocities correctly. The reason is that for a pulsar born in the central bulge of the galaxy with an initial velocity of order 500 km/s, it will take about 3 Myr to travel the distance of 10^3 pc characteristic of the size of the central bulge. Therefore, only pulsars with high birth velocities would have emerged from the galactic core (and from behind the bulge) during the first 3 Myr after birth. The pulsars with lower birth velocities would still be hidden behind the stellar matter in the core and their signal would not reach the Earth. If the birth velocities of the pulsars are, in fact, correlated with their magnetic fields, one would expect only the pulsars with large magnetic fields to be observable during the first 3 Myr after birth. This is consistent with the data presented by Lorimer, Lyne and Anderson in figure 1(c) of their recent paper [10] on the $B - v$ correlation. Although, for the reasons just mentioned, we do not consider the sample of younger pulsars a good representative for the distribution of birth velocities, we emphasize that the effect in question is evident for the subset of young pulsars, as well as for the entire set.

Finally, the increase in $B - v$ correlation with P could be attributed to some kind of a selection effect if the rotation periods of the pulsars in our sample were correlated with their ages. It is reassuring, therefore, that there is no such correlation among the 87 pulsars we have considered.

We have implicitly assumed that the magnetic field inside the neutron star, between the electron and τ -neutrinospheres, is proportional to the magnetic field at the surface. This is a plausible assumption [12] but cannot be verified experimentally. If the magnetic field outside the neutron star is not a good measure of the fields strength inside, this could be the source of additional smearing of the $B - v$ correlation.

In summary, the substantial increase in the $B - v$ correlation for the slowly rotating pulsars lends further support to the recently proposed explanation of the pulsar birth velocities based on neutrino oscillations [8]. The most significant correlation occurs for slowly rotating pulsars, while the overall $B - v$ correlation is obscured by the inclusion of both slow and fast rotating pulsars in the analysis.

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